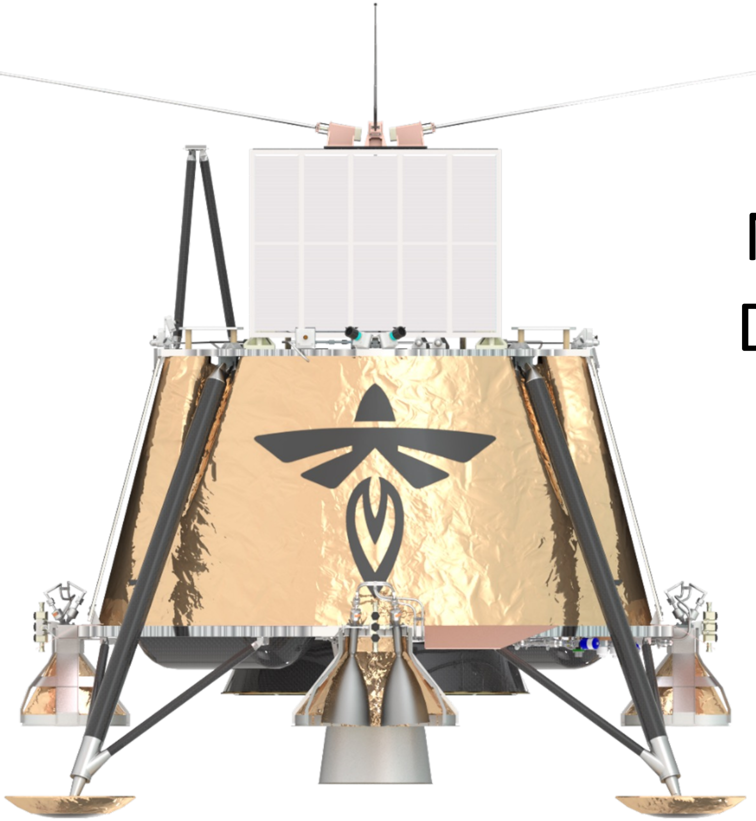
The Lunar Surface Electromagnetics Experiment
LuSEE ‘Night’

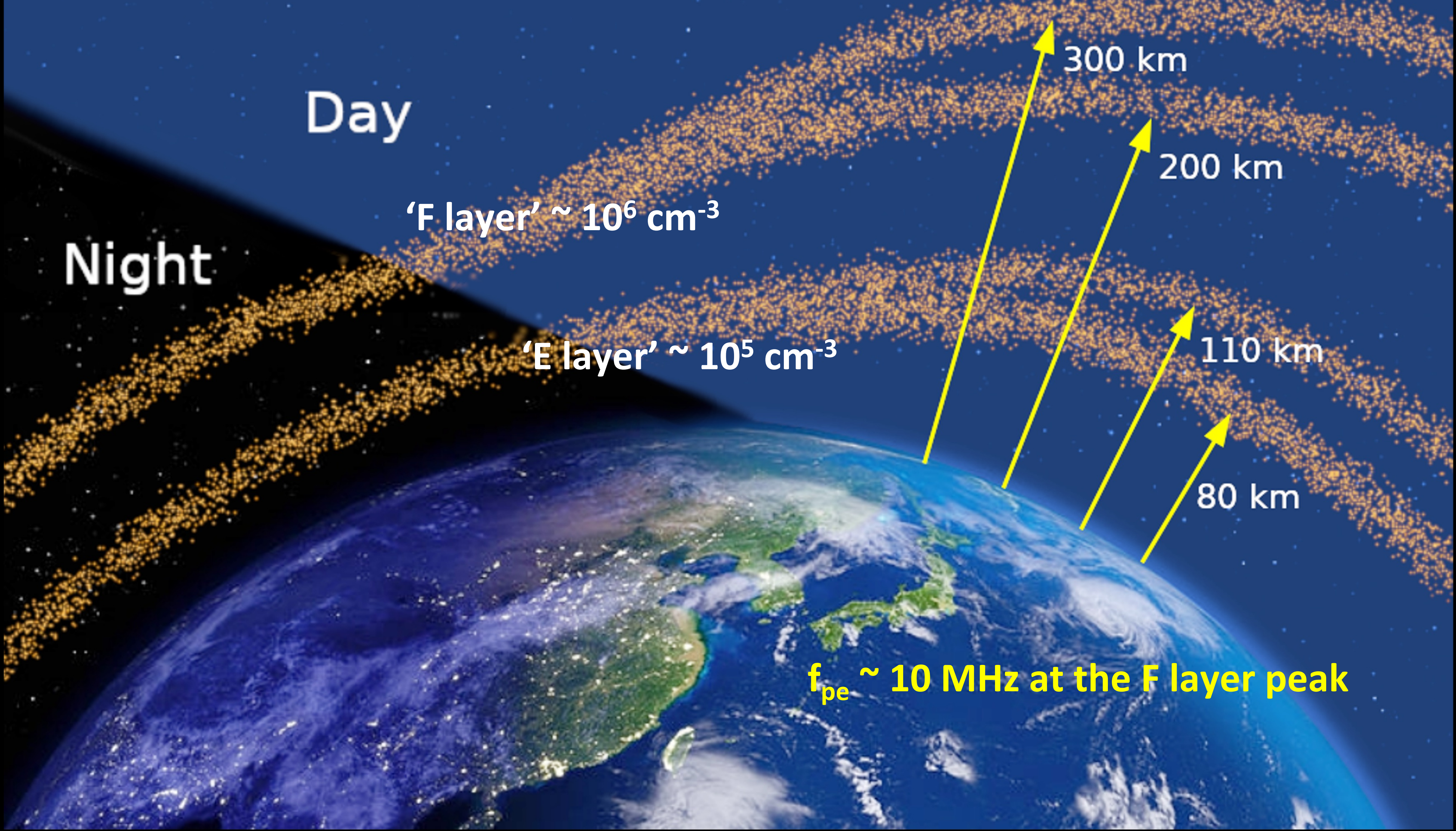


NASA PI: Stuart D. Bale (UC Berkeley)
DOE Spokesperson: Anže Slosar (BNL)

Summary: LuSEE Night is a *simple* LF radio astronomy experiment for the lunar farside and a pathfinder for Dark Ages radio cosmology

- Low frequency (< 50 MHz) radio astronomy from space
  - Ionosphere and lightning
  - Noisy human beings
  - Spacecraft electromagnetic interference
  - Science
- The Lunar Surface Electromagnetics Experiment (LuSEE) program
  - LuSEE ‘Lite’
  - LuSEE ‘Night’
- Farfield calibration source
- Signal extraction and data pipeline

The terrestrial ionosphere



Lightning and VHF radio

39 MHz at 800 km altitude

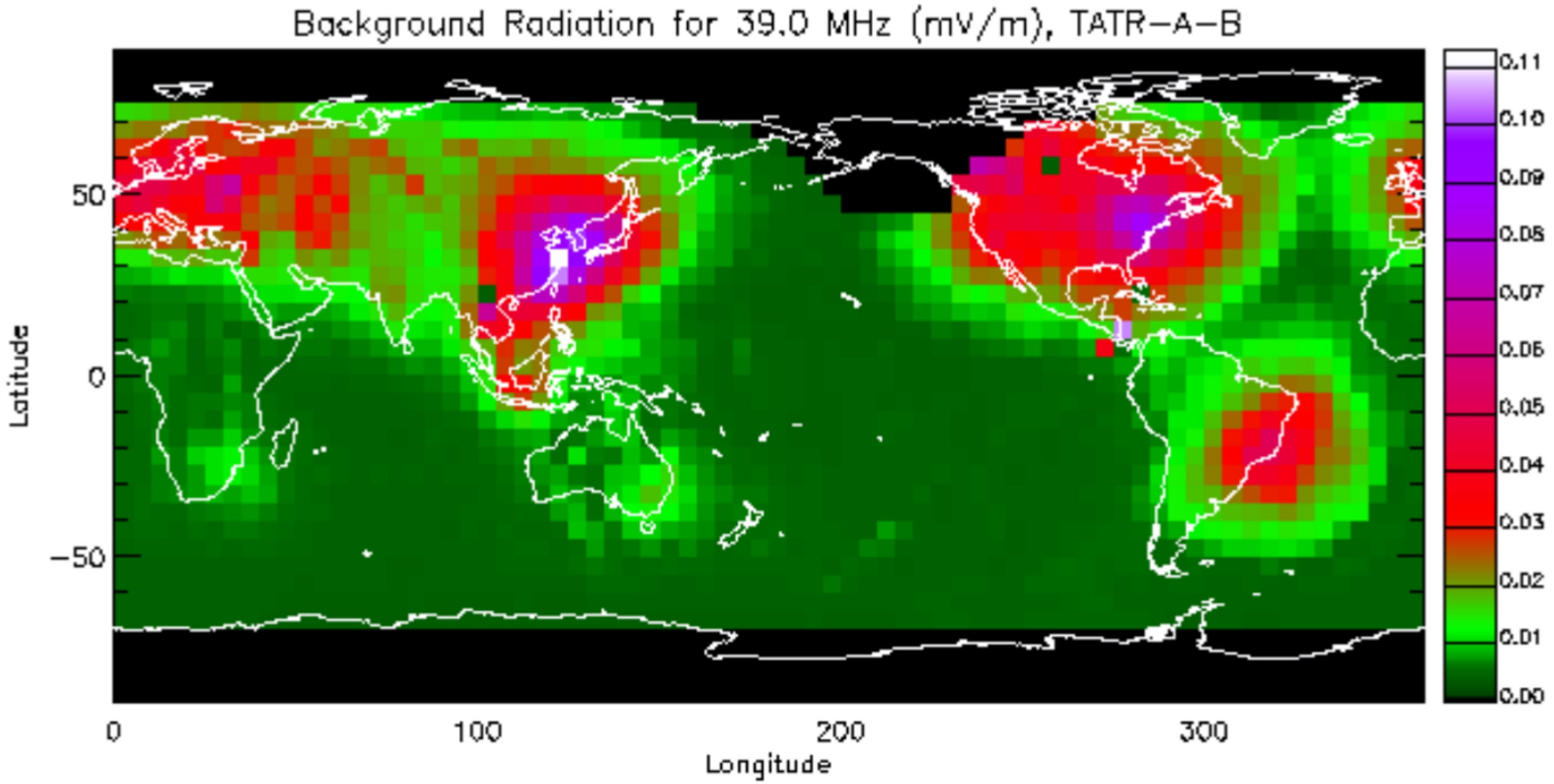
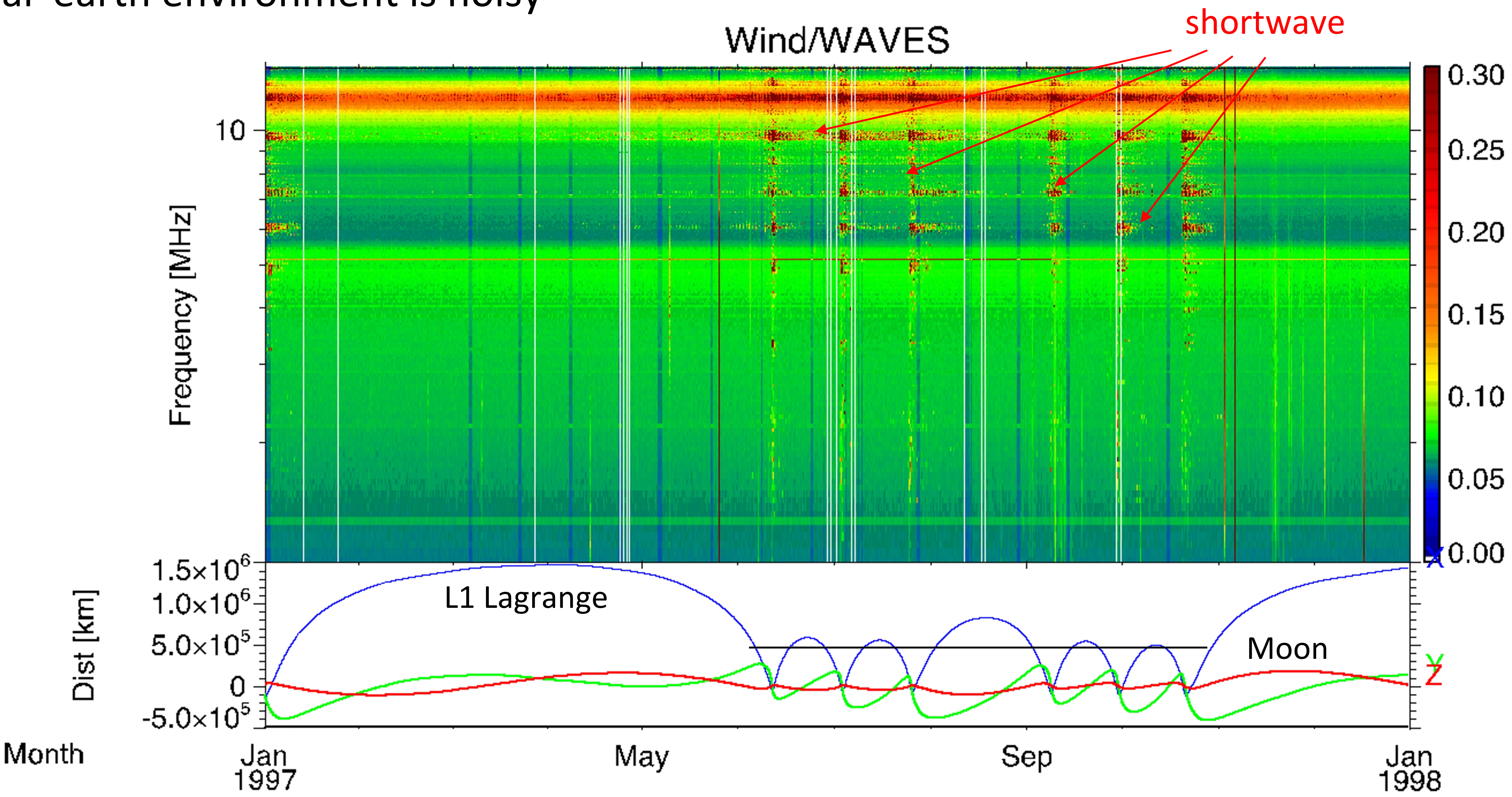


Figure 7: *A FORTE compilation of global VHF noise levels, in mV per m per MHz (1 mV/m = 2.6 nW/m^2), as observed from an 800 km altitude. The lowest levels (green) are consistent with Galactic background noise, and occur in the Southern Ocean and along the Antarctic coast.*

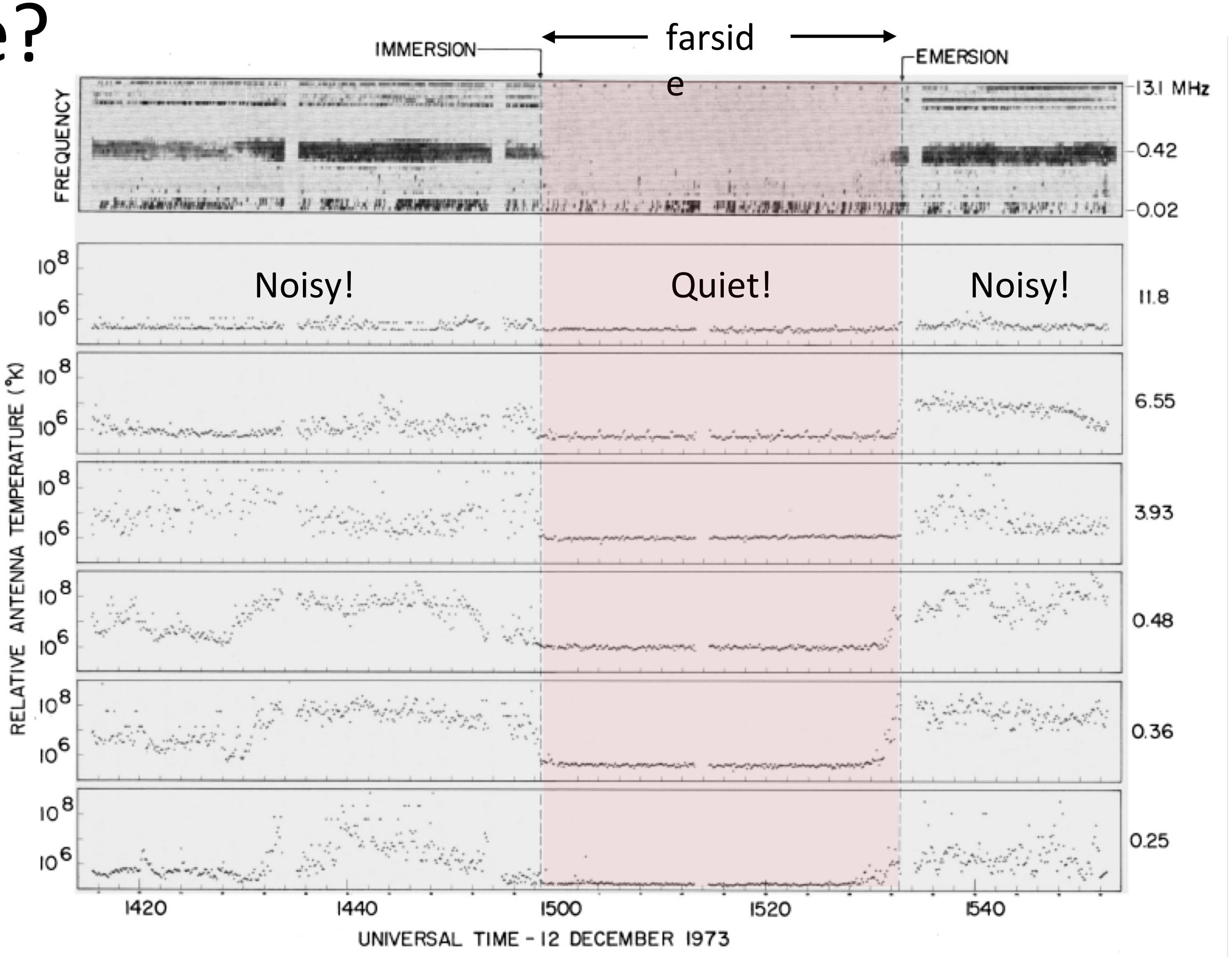
One year of < 14 MHz measurements near earth, solar minimum
Near-earth environment is noisy



Why the lunar farside?

The lunar farside (*still*) offers radio-quiet intervals shielded from Earth (**always**) and the Sun (**monthly**) and outer planets (**regularly**).

- A long history of concepts.
- The Chinese Chang'e 4 Instrument

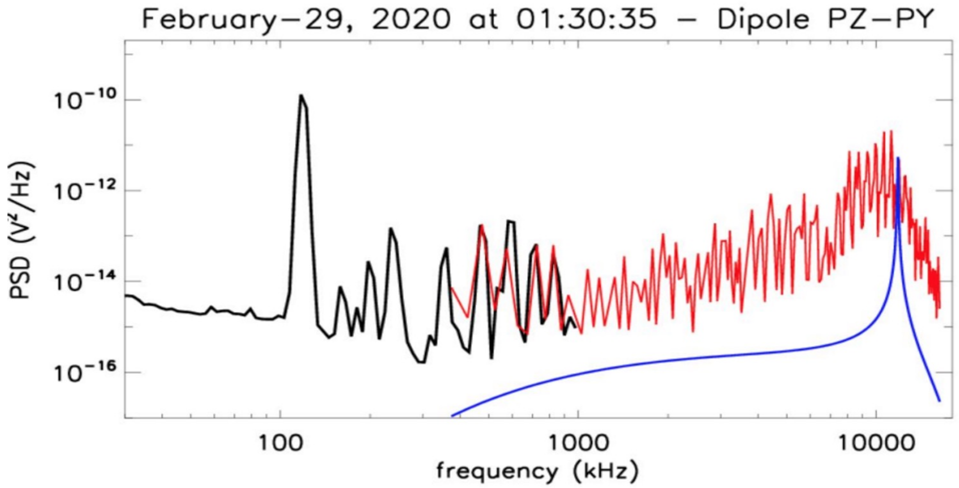


(RAE-2 spacecraft, Alexander et al., 1975)

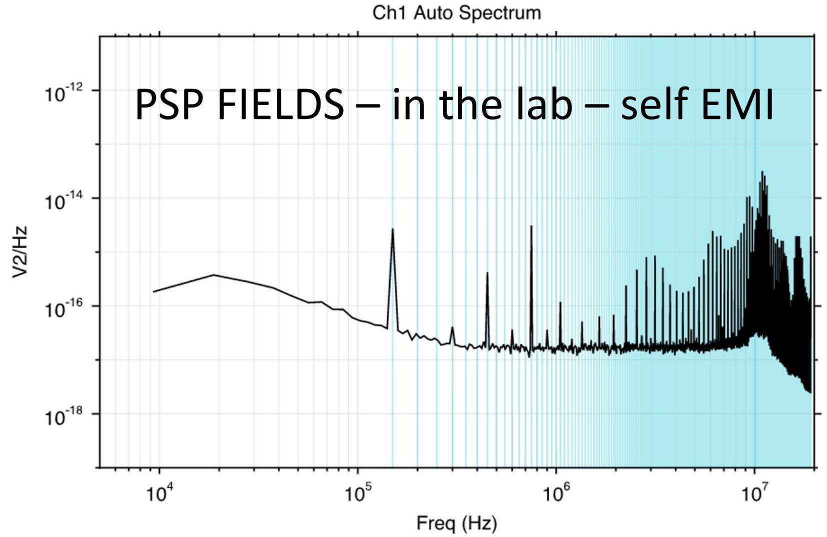
Spacecraft Electromagnetic Compatibility (EMC)

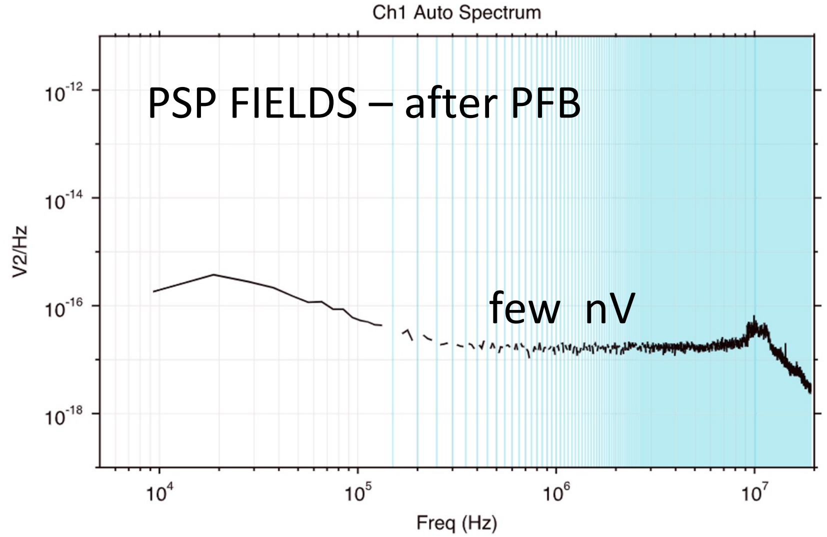
- NASA *Parker Solar Probe* 'FIELDS' Instrument
- 'Picket fence' approach to ***entire*** system
    - 150 kHz + n*50 kHz
- 10-100 ppm frequency stability on *all* oscillators (DC-DC power converters)
- Crystal-controlled oscillators
- Polyphase Filter Bank (PFB) signal processing

ESA Solar Orbiter RPW measurements



(Maksimovic et al., 2021)





PSP measurements: galactic foreground and spatial structure

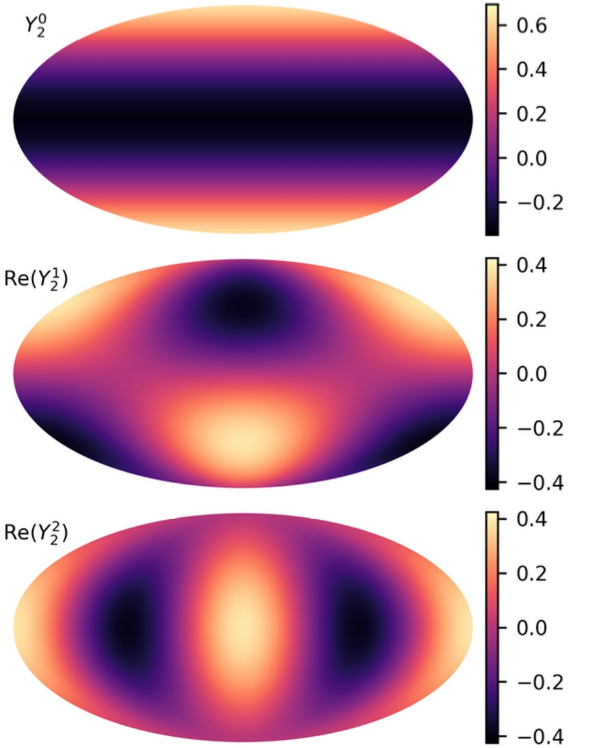


Fig. 5. Mollweide projections of the $l = 2$ spherical harmonics. We evaluate their amplitudes in the Galactic coordinate system, in which the diagram centers and tops are, respectively, $(b_g, l_g) = (0°, 0°)$ and $b_g = 90°$. With l_g decreasing from left to right, the imaginary parts of Y_2^1 and Y_2^2 are given by rotations of the real parts about the downwards pointing axes by $90°/m$.

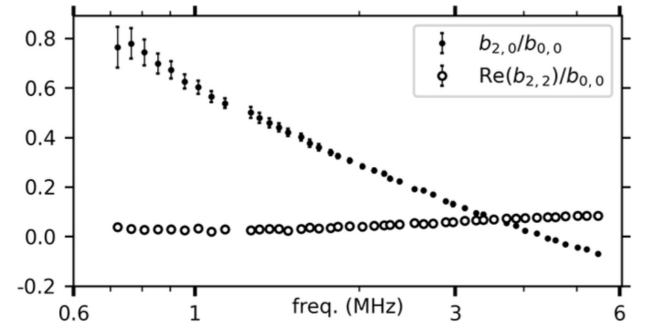


Fig. 6. Solutions for $b_{2,0}$ and $\mathrm{Re}(b_{2,2})$ from Fig. 4 normalized by measurements of the isotropic brightness $b_{0,0}$ from PSP. Most of the error bars cannot be seen because they do not extend beyond the plot markers.

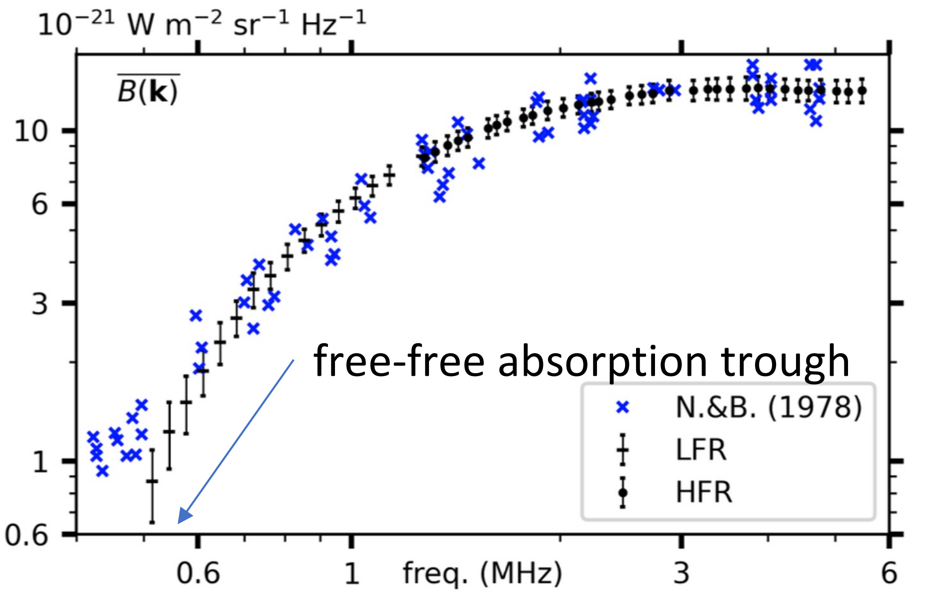
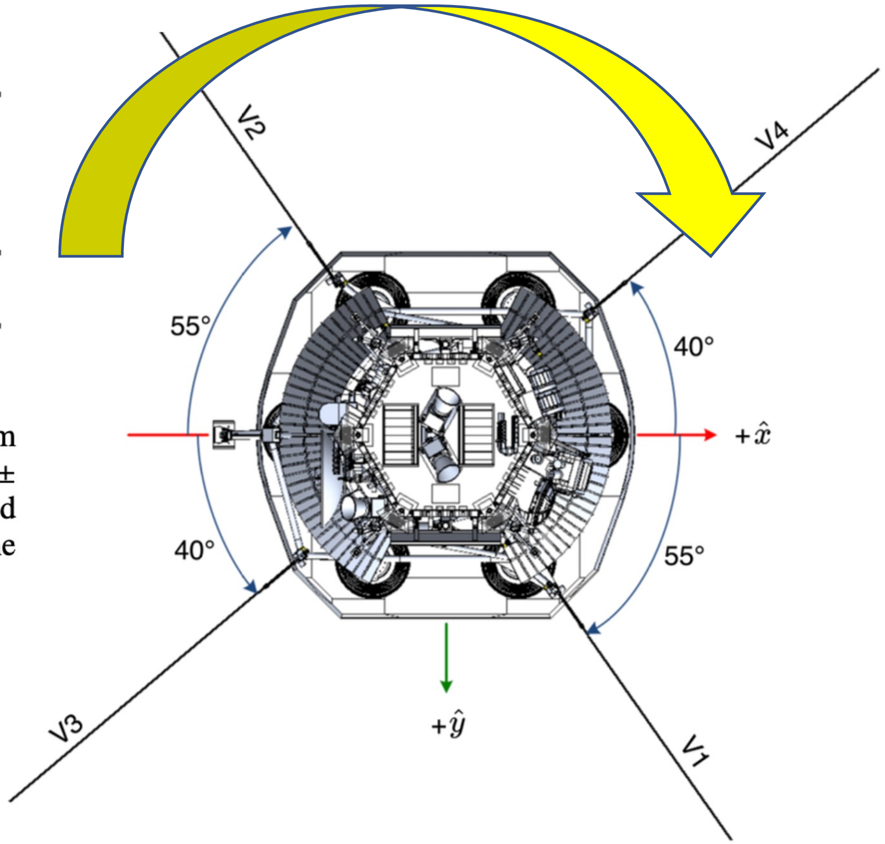


Fig. 3. Mean sky intensity measurements from PSP scaled to data from Novaco & Brown (1978) using effective antenna lengths, $L_{12} = 3.3 \pm 0.1$ m and $L_{34}/L_{12} = 0.99 \pm 0.01$, that minimize the summed squared residuals between the data sets. The relative uncertainty on most of the Novaco & Brown (1978) points is between 15 and 20%.

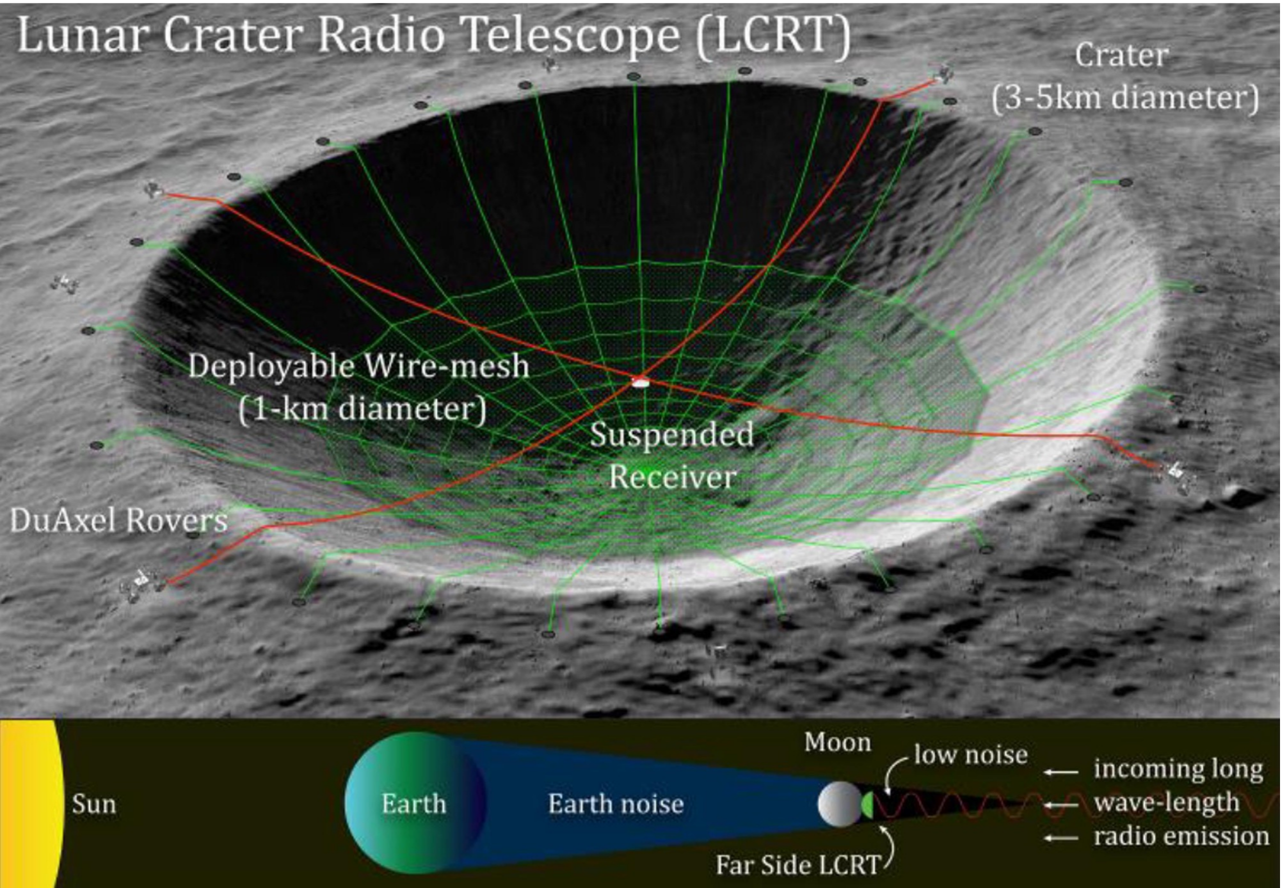
(*Page et al., 2022; Bassett et al., 2023*)

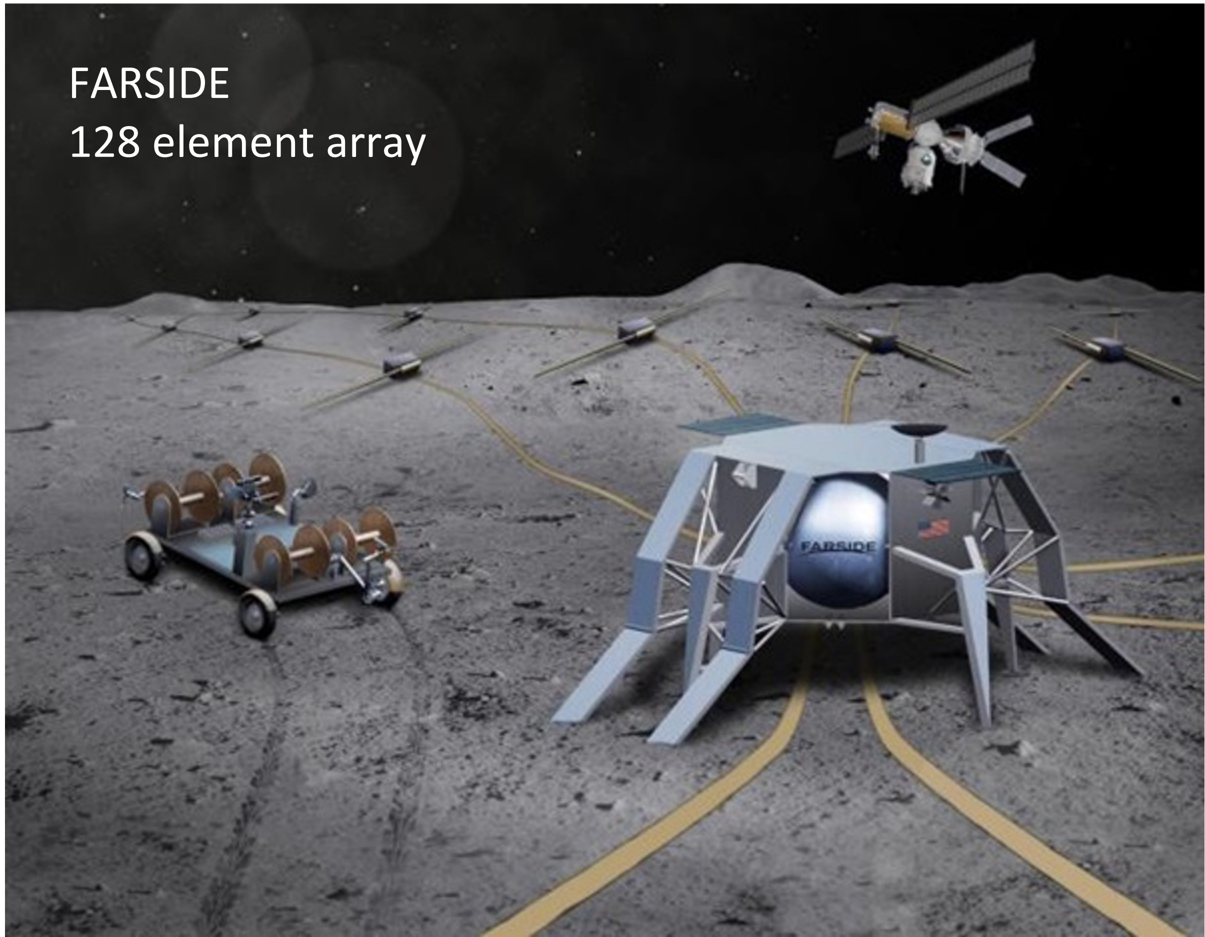
Galactic structure will introduce chromaticity to a simple beam



Radio Astronomy on the lunar farside

21cm radio cosmology

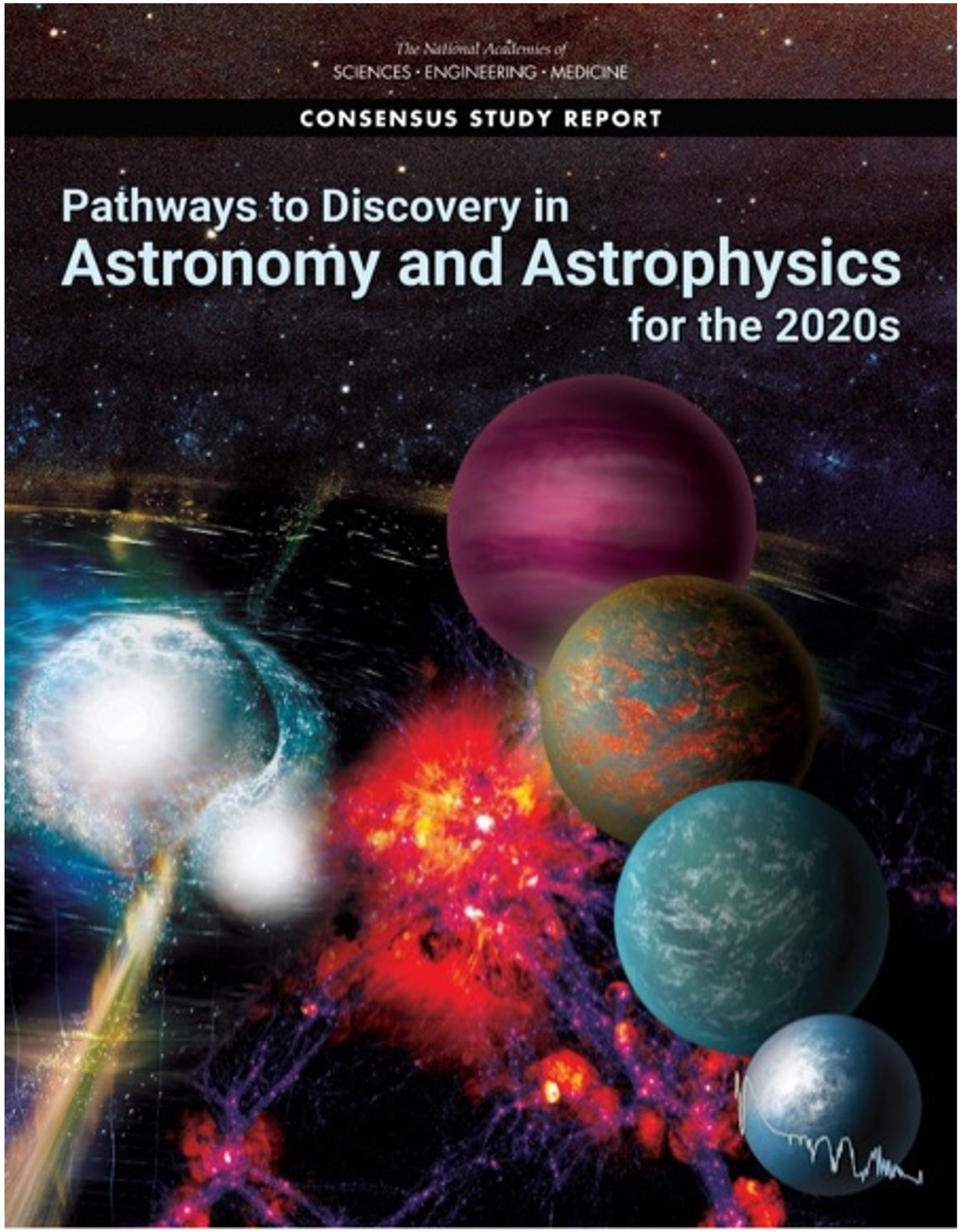




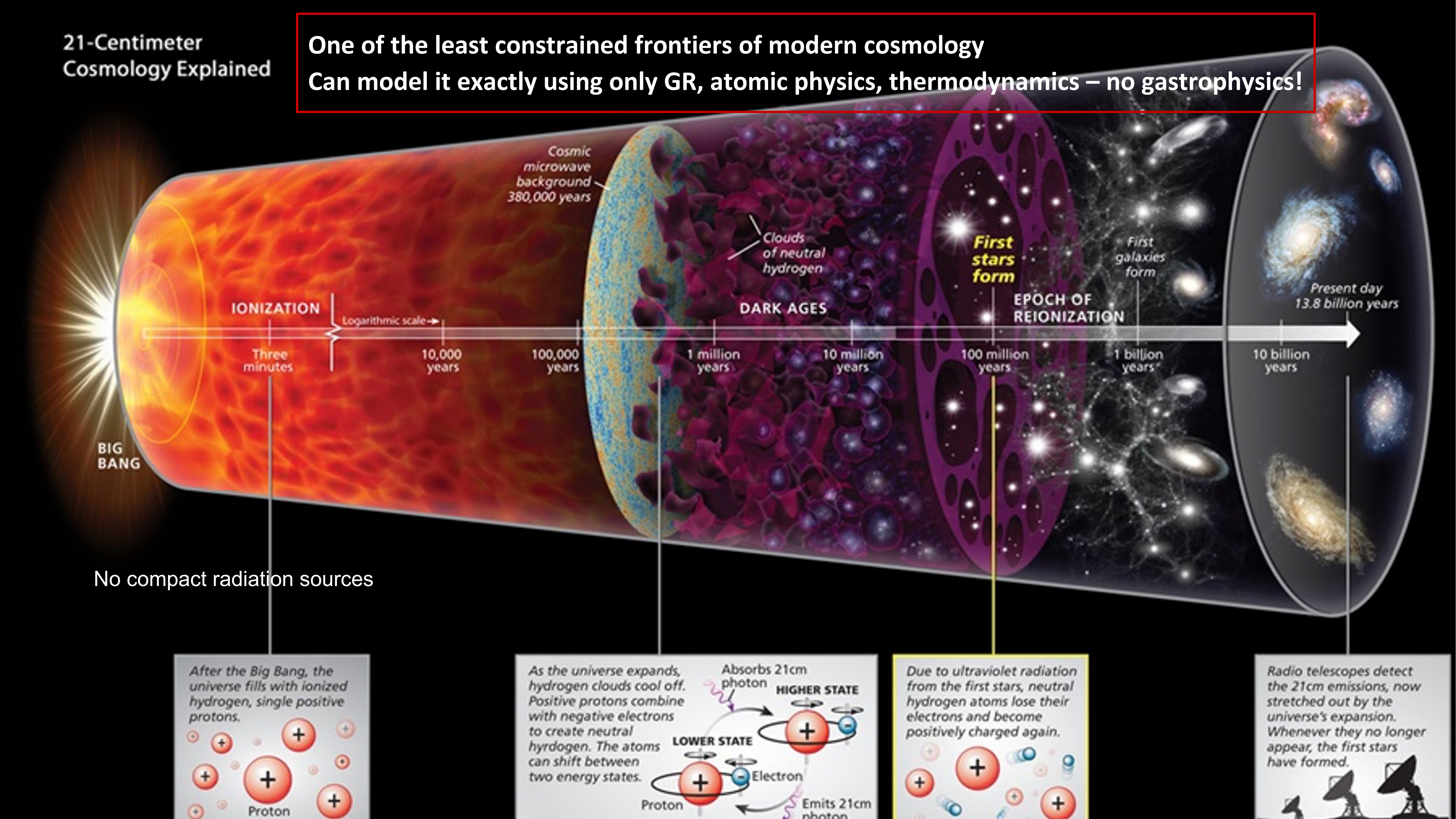
Decadal Survey on Astronomy & Astrophysics, Panel on Cosmology p.258

DISCOVERY AREA: THE DARK AGES AS A COSMOLOGICAL PROBE

"The panel sees 21 cm and molecular line intensity mapping of the Dark Ages and reionization era as both the discovery area for the next decade and as the likely **future technique for measuring the initial conditions of the universe in the decades to follow**.



One of the least constrained frontiers of modern cosmology
Can model it exactly using only GR, atomic physics, thermodynamics – no gastrophysics!



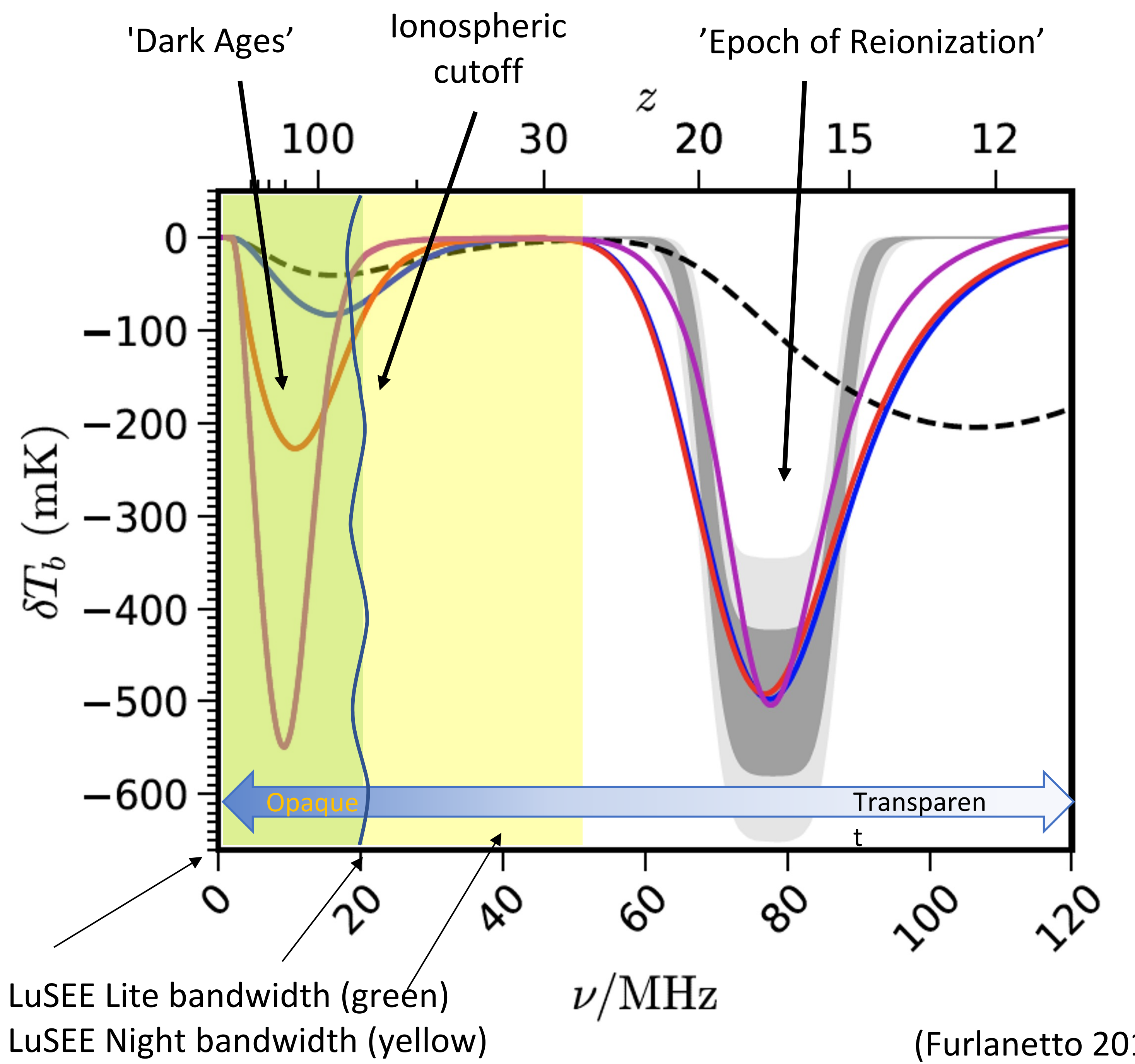
No compact radiation sources

This is challenging…

RFI environment aside…

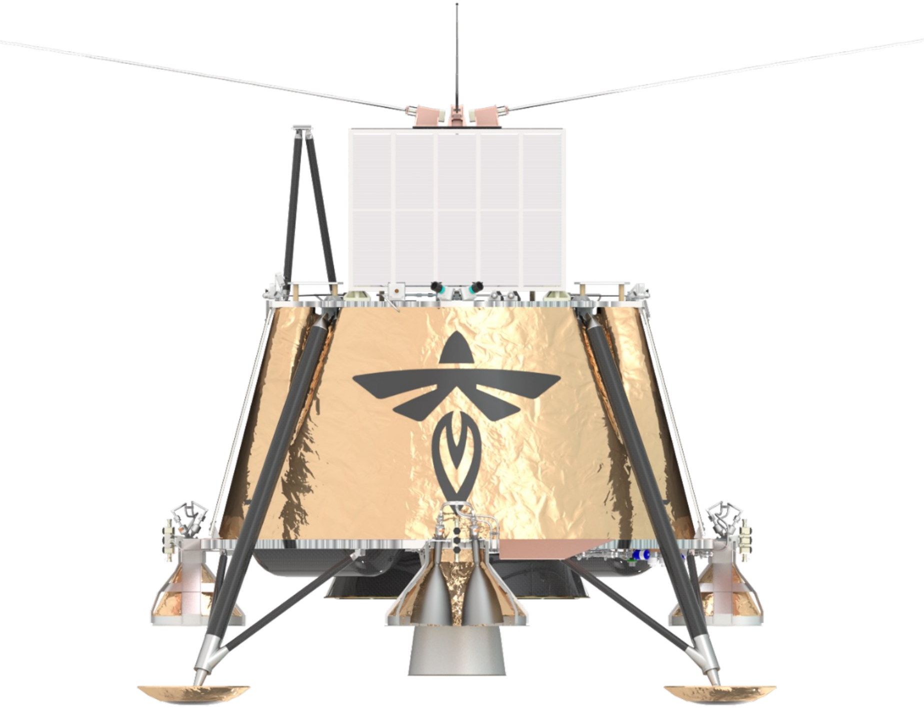
- The 21cm signature should be 50-500 mK
- The galactic foreground is ~10^5 K
- The transient foreground (Sun, planets) can be 100x galactic foreground
- The 21cm spectral feature is spectrally broad

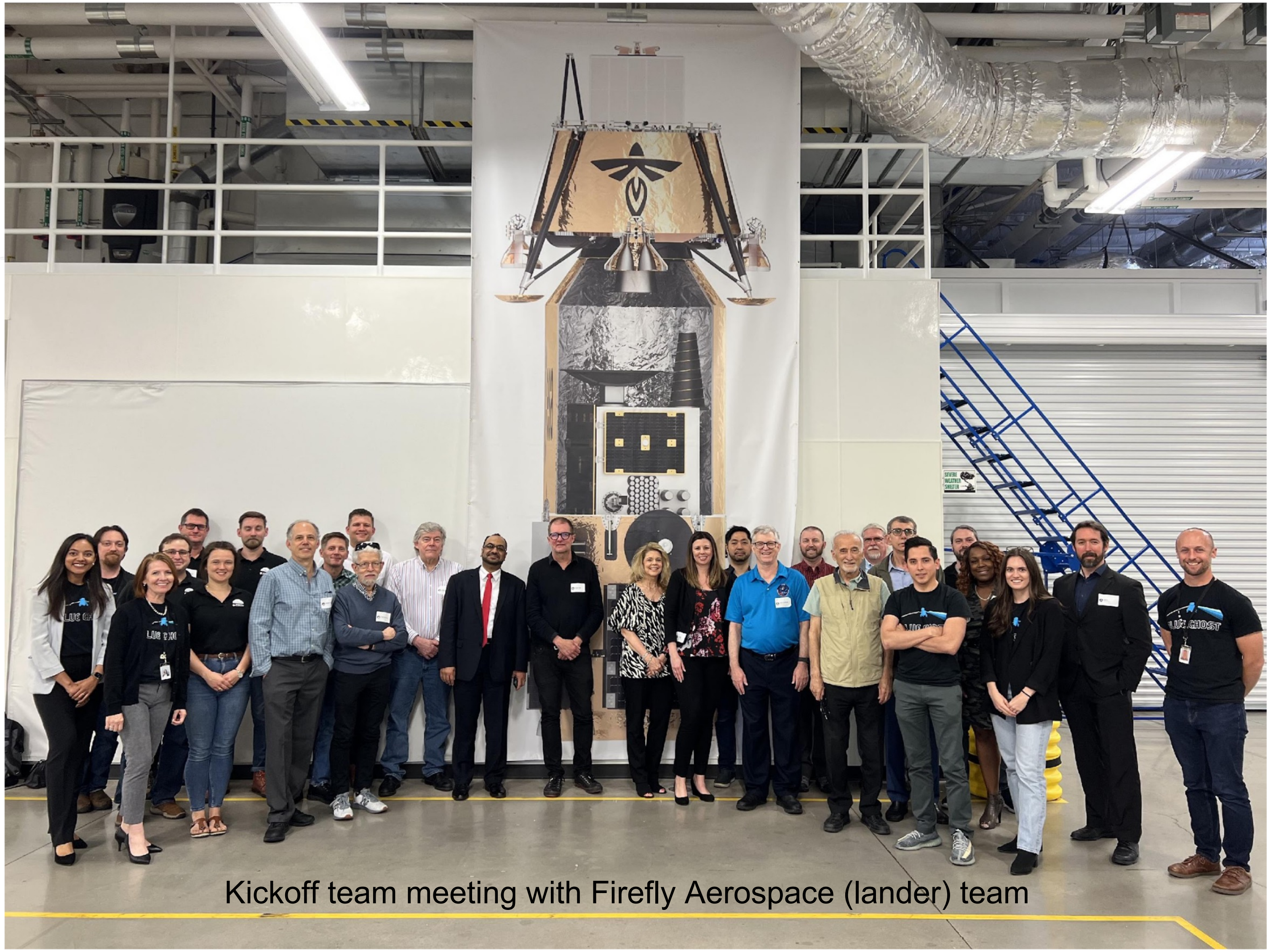
- There is also bleeding-edge solar and planetary physics at hand!



(Furlanetto 20

LuSEE 'Night'





Kickoff team meeting with Firefly Aerospace (lander) team

NASA PI: Stuart D. Bale (UC Berkeley)
DOE Spokesperson: Anže Slosar (BNL)

ArXiv manuscript: https://arxiv.org/abs/2301.10345

- LuSEE was **selected** in June 2019 by NASA in the Lunar Surface Instrument and Technology Payloads (**LSITP**) for the Commercial Lunar Payload Services (**CLPS**) program – *originally based on flight spare hardware from the **NASA Parker Solar Probe 'FIELDS' instrument***

- Under contract by MSFC/PMPO and **in development**

- LuSEE is a *program* **split into 2 payloads on 2 separate landers**

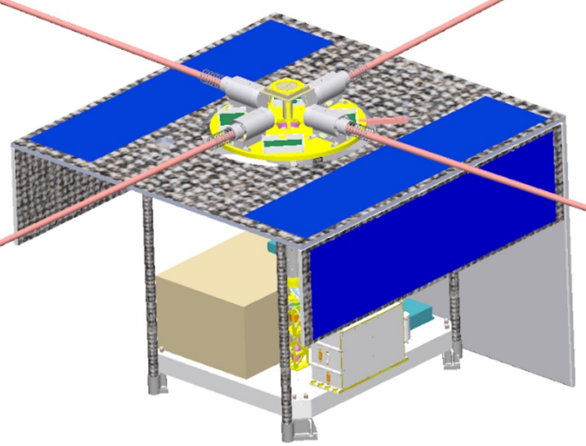
  - **LuSEE 'Lite'** (CP-12) to the Schrödinger Basin (south pole farside) in 2025 on the CP-12 mission
    - Surface plasma physics and waves, **20 MHz radio**, DC electrostatic potentials, dust impacts, and joint measurements with LITMS/LMS (magnetotellurics)

  - **LuSEE 'Night'** (CS-3) to the farside mid-latitudes in Q4/2025-Q1/2026 window on the CS-3 mission in a strategic initiative with the US Department of Energy (DOE) – Brookhaven National Lab (BNL) and Lawrence Berkeley Lab (LBL)
    - Low frequency radio astronomy (< ~50 MHz) pathfinder with **standalone** operations through the lunar night, Lunar farside landing site, mid-latitudes
    - Operations through the lunar night, full EMI control, lander is **dead**
    - NASA instrument funding MSFC/PMPO, DOE MIE, NASA CLPS lander

LuSEE Night Payload

- 3m BeCU stacer antennas (6m t-t) with turntable to change orientation
- ~50 MHz bandwidth, 4-channel baseband receiver
- Far-field calibration source (CLPS CS-4 mission)
- ESA Lunar Pathfinder (LPF) comms – 6+ GB/night
- Daytime comms, charging, turntable ops

(no lander shown)



- Late 2025/early 2026 landing
  - Outer planets
- Lander will **die** after commissioning
  - No spacecraft EMI!
- Landing site selected
  - Mid-latitudes
  - Farside
  - Slightly south

Standalone system

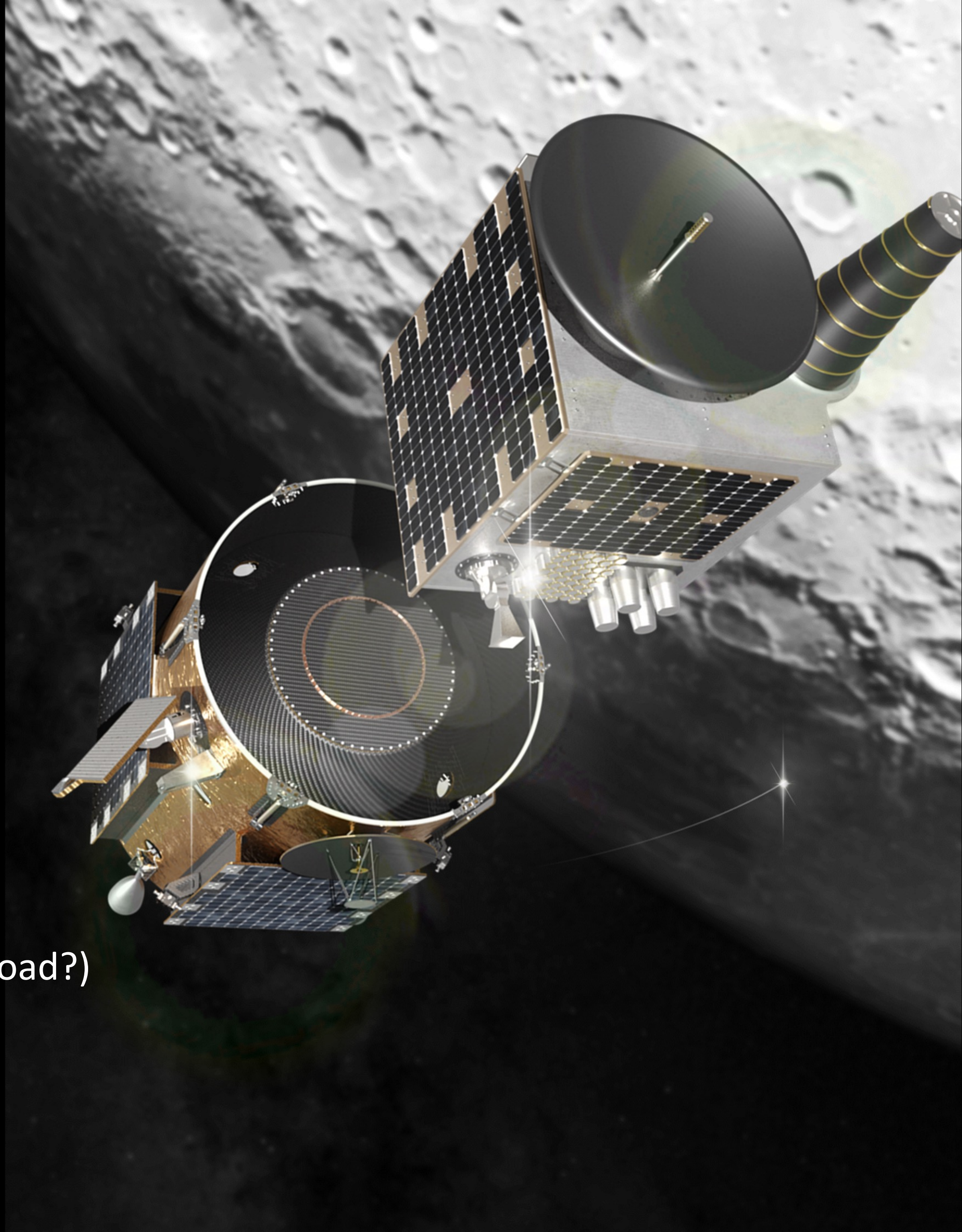
- Instrument electronics
- Solar arrays
- ~43kg battery - ~15W operational power = heat
- S-band Comms (JPL/Vulcan User Terminal)
- PRISM FSS-like (JPL PALETTE) thermal design

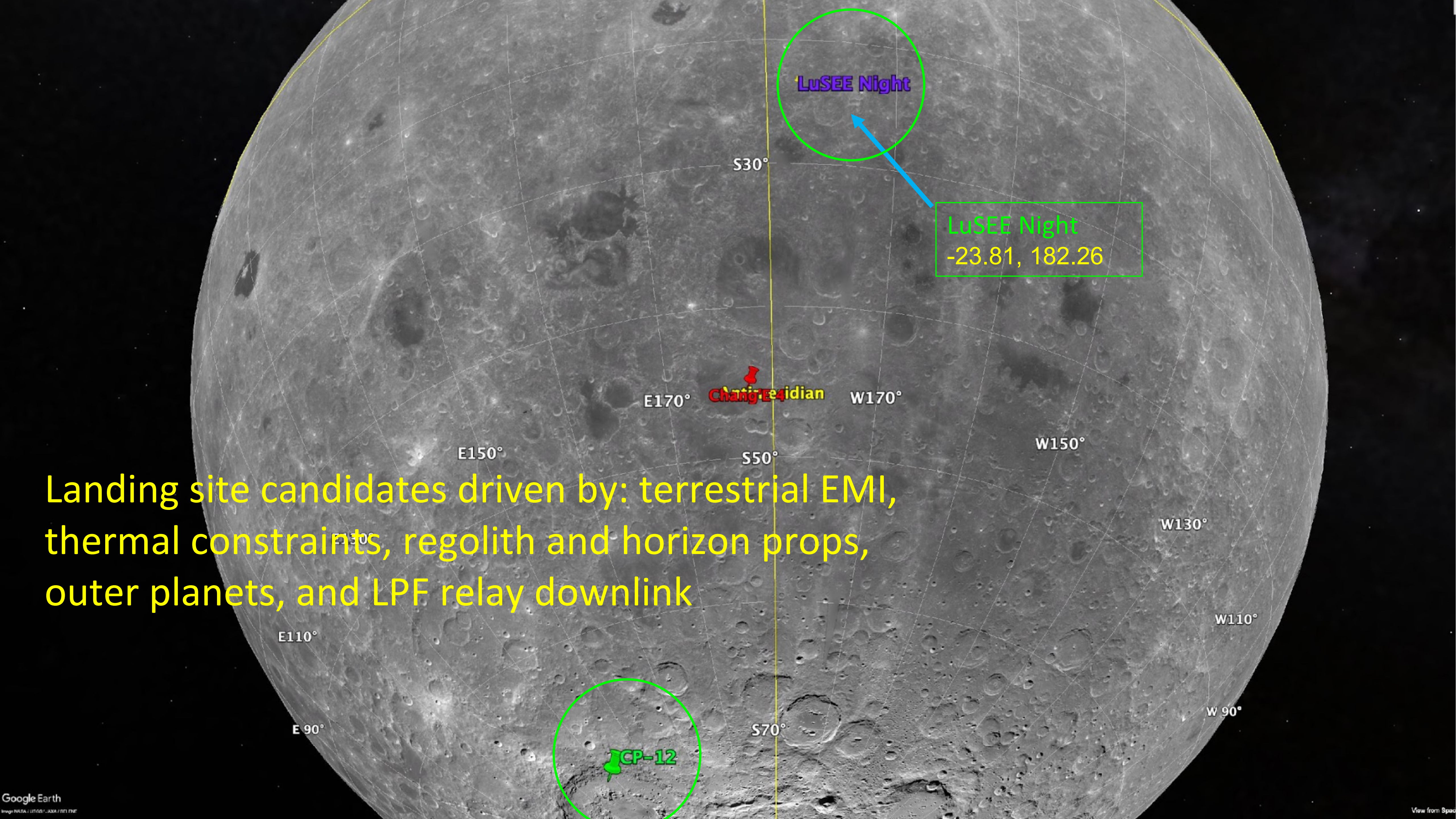
The CLPS ‘CS-3’ Mission

- Launch – December 2025 on Falcon 9
- Landing – January 2026

Firefly Aerospace

- Blue Ghost Lander (with LuSEE Night)
- Blue Ghost Transfer (w/ commercial payload?)
- ESA Lunar Pathfinder (LPF) relay satellite
- S-band and UHF comms

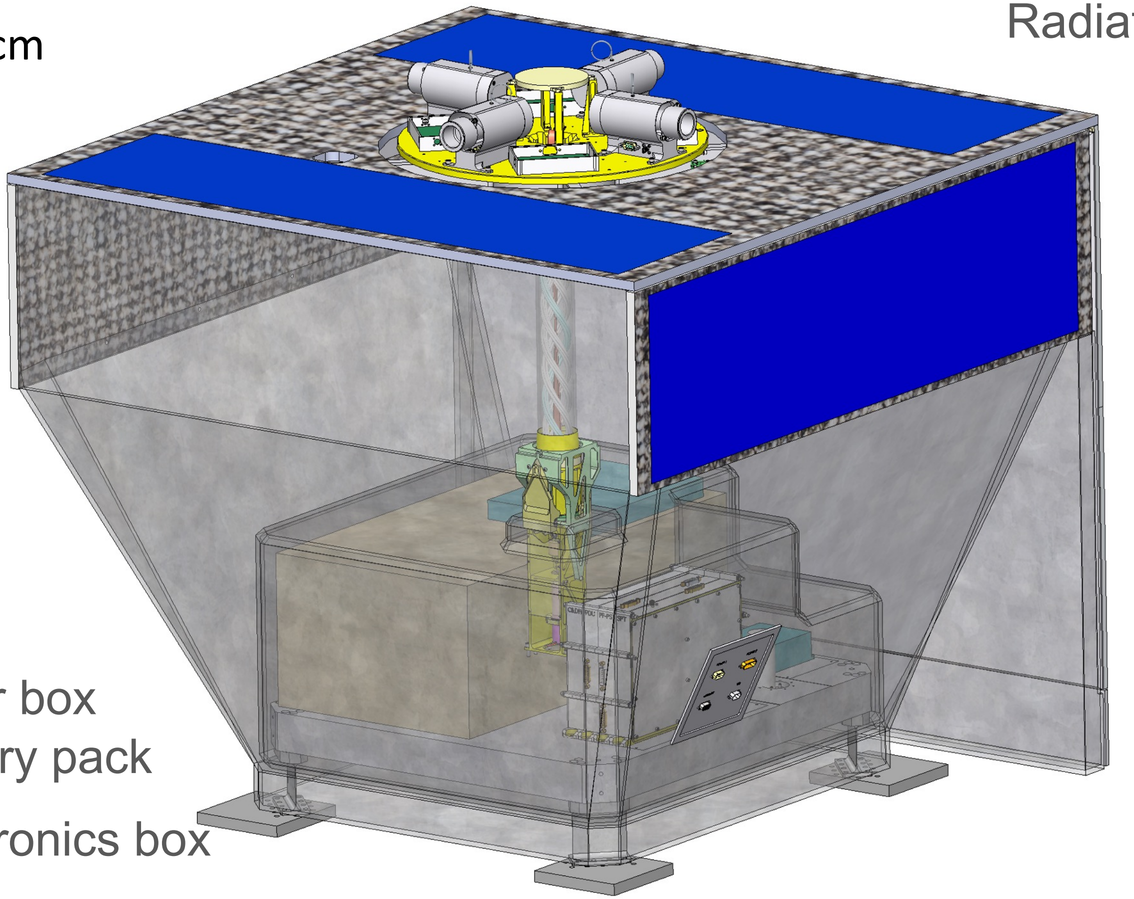




Landing site candidates driven by: terrestrial EMI, thermal constraints, regolith and horizon props, outer planets, and LPF relay downlink

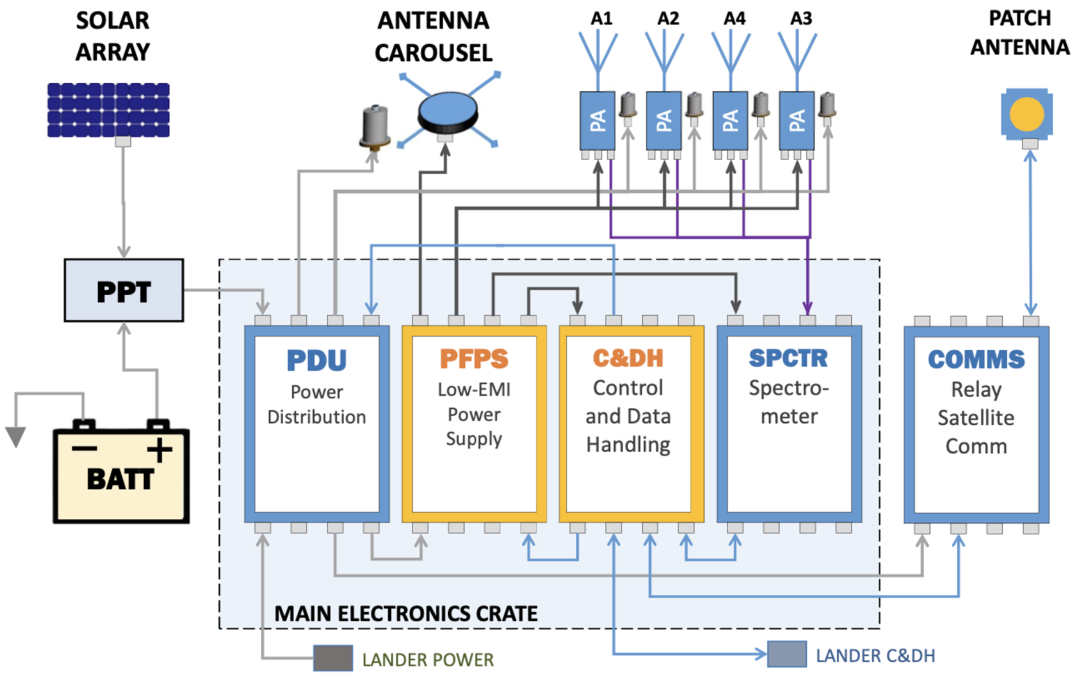
LuSEE Night and 'Blue Ghost' on the Moon

LuSEE Night System Design



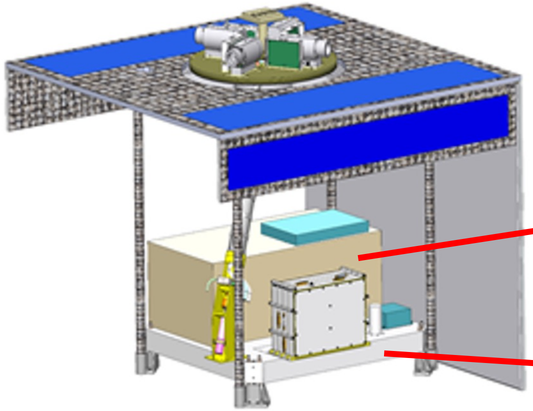
- Outer box
- Battery pack
- Electronics box

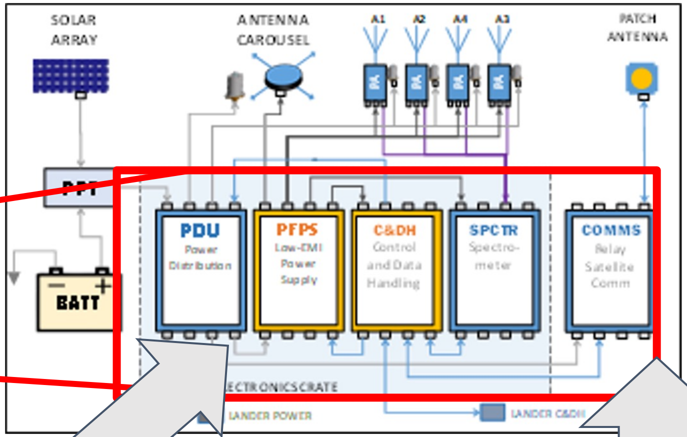
Spectrometer – BNL
Antennas – LBNL (w UCB)
DCB-CSAC/Power – UCB and UMN from PSP design
Comms – JPL/Vulcan



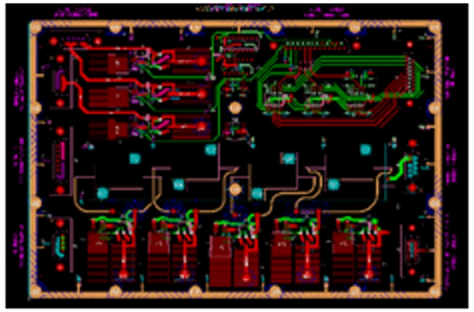
Voltage measurement

Electronics Board Status



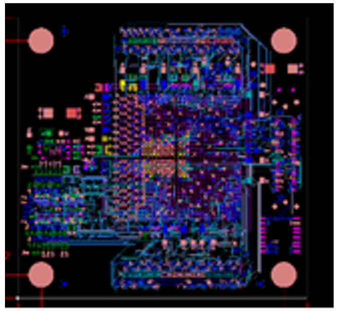


PREAMP
(tested)



POWER DISTRIBUTION
(in fab)

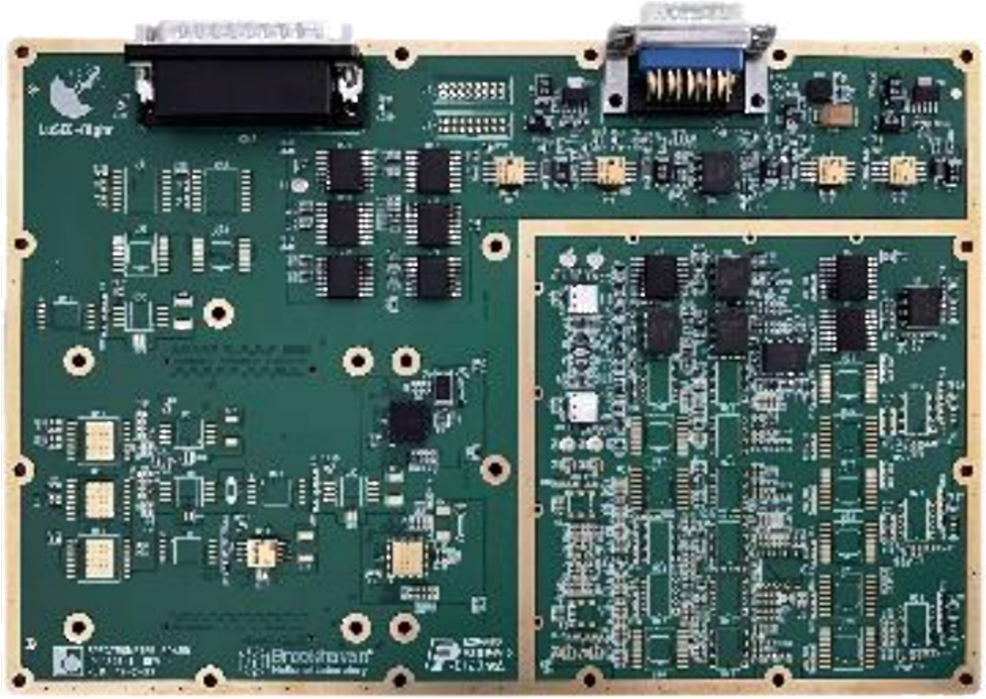
SPECTROMETER
(tested)



COMMS (in fab)

Spectrometer design

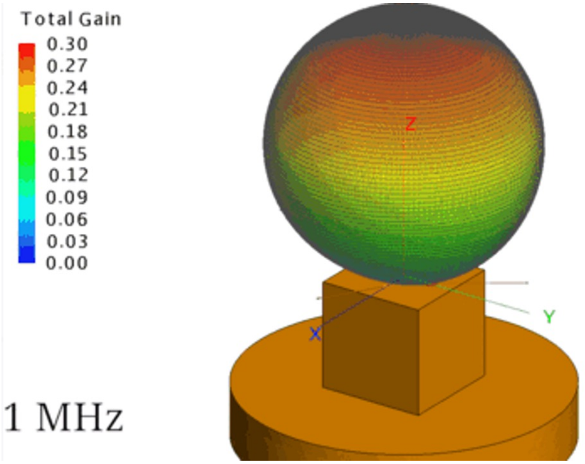
- Spectrometer is at the heart of the instrument
- Nominally 2048 channel polyphase filter-bank
- Our design strongly based on the Parker Solar Probe/FIELDS Radio Frequency Spectrometer (RFS)
- Significant improvement in performance:
  - 2 → 4 channels
  - 4 → 16 correlation products
  - 20 → 50 MHz bandwidth
  - 1% → 100% duty factor
  - Notch filters for RFI
  - New data products for zoom and calibrator support
- ~200x improvement in performance at approximately the same power draw
- Excellent demonstration of synergies between NASA space know-how and DOE DSP heritage



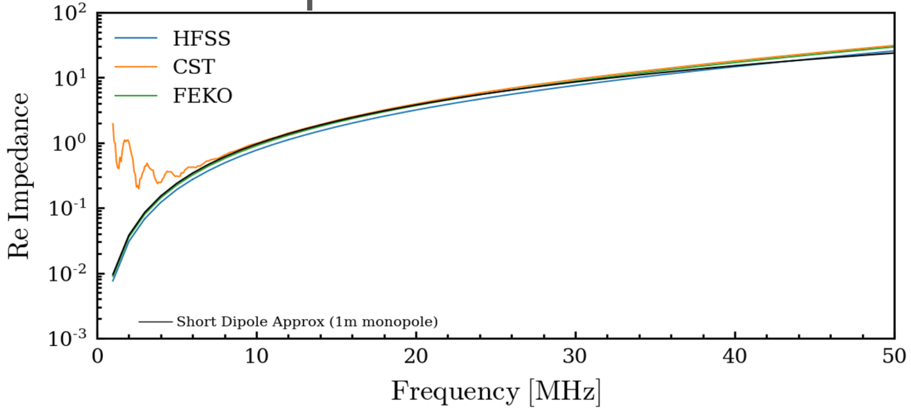
Current devel version runs full 51.2MHz bandwidth, 2-input, 2048 channel spectrometer on <0.6W.

Antenna properties

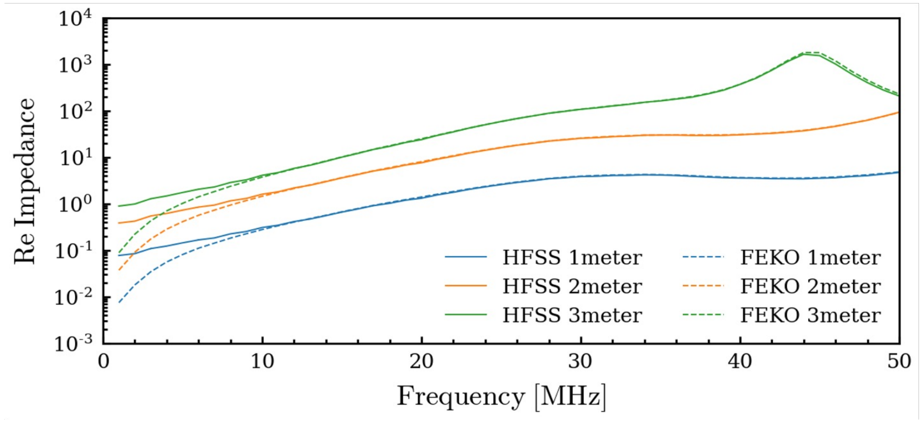
- We performed extensive numerical simulations of the antenna subsystem
- comparing numerical methods
- optimizing antenna parameters
- understanding the effect of the lander and regolith on the antenna pattern

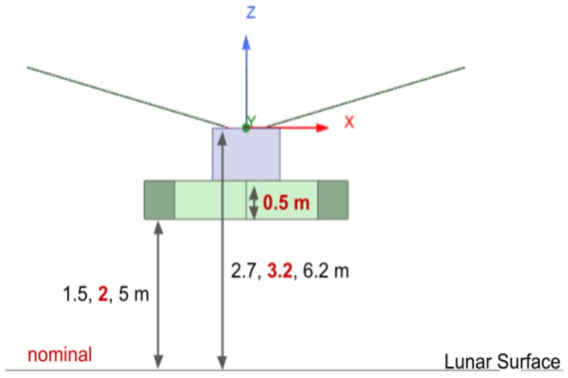


Dipole in Vacuum



LuSEE on Moon

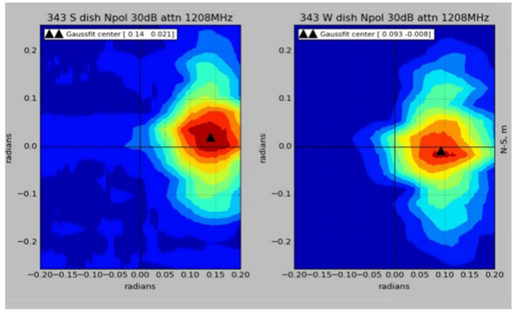




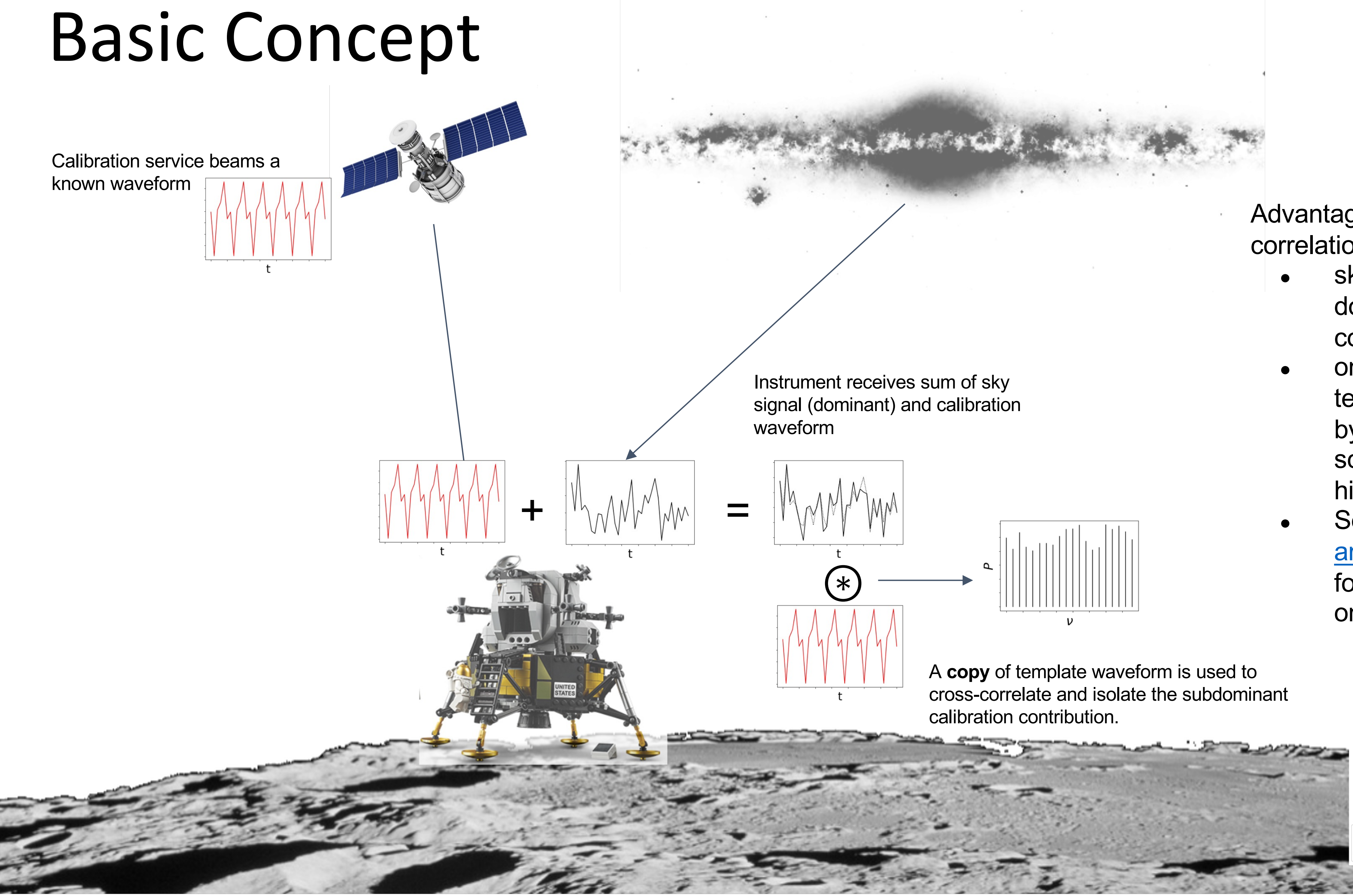
(Kaja and Toki at LBL)

Far-field Calibrator

- Field of 21cm is a study of calibration methods
    - Foregrounds many times brighter
- Precision calibration of radio telescope beams at sub-percent precision remains to be demonstrated
- Many attempts with drones, but nobody has reached required precision
- At frequencies below 50MHz particularly hard- beams are very large and non-steerable
- no point sources with well calibrated flux
- **A true far-field, power stabilized calibrator is almost certainly necessary for dark ages work**:

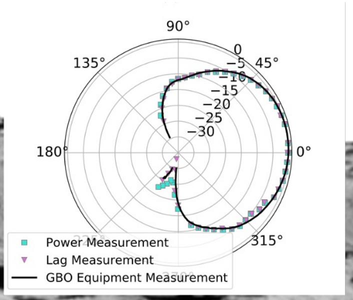


Basic Concept



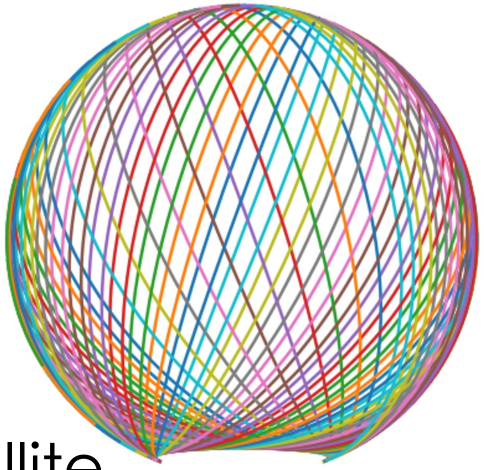
Advantages of cross-correlation technique:

- sky background does not cross-correlate
- only one copy of template attenuated by the distance (1/r scaling), allowing high SNR recovery
- See arXiv:2201.11806 for similar approach on the ground

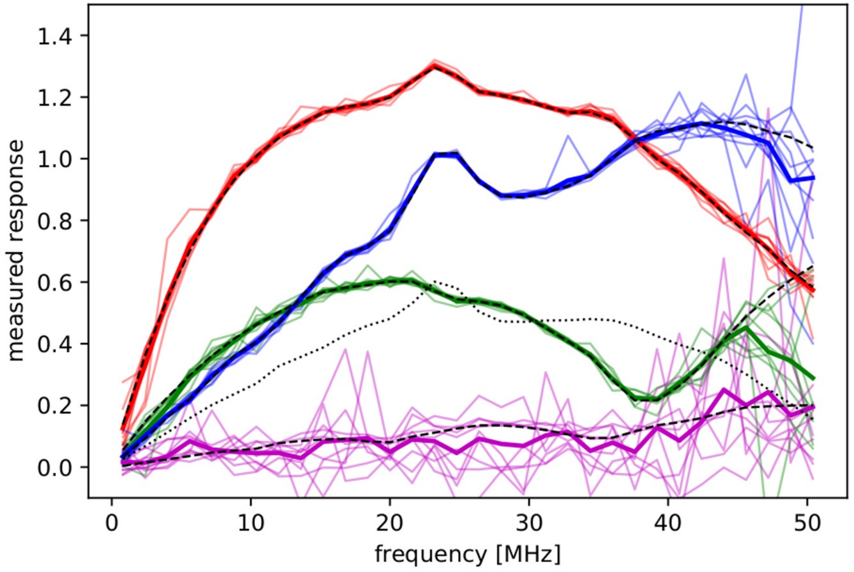


Calibrator status

- CLPS CS-4 mission is for *provision of calibration service*
- Currently in the process of seeking bids
- NASA will choose the best value technically satisfactory bid (provided it fits the budget)
- We're waiting for the outcome of this process (~May 2023)

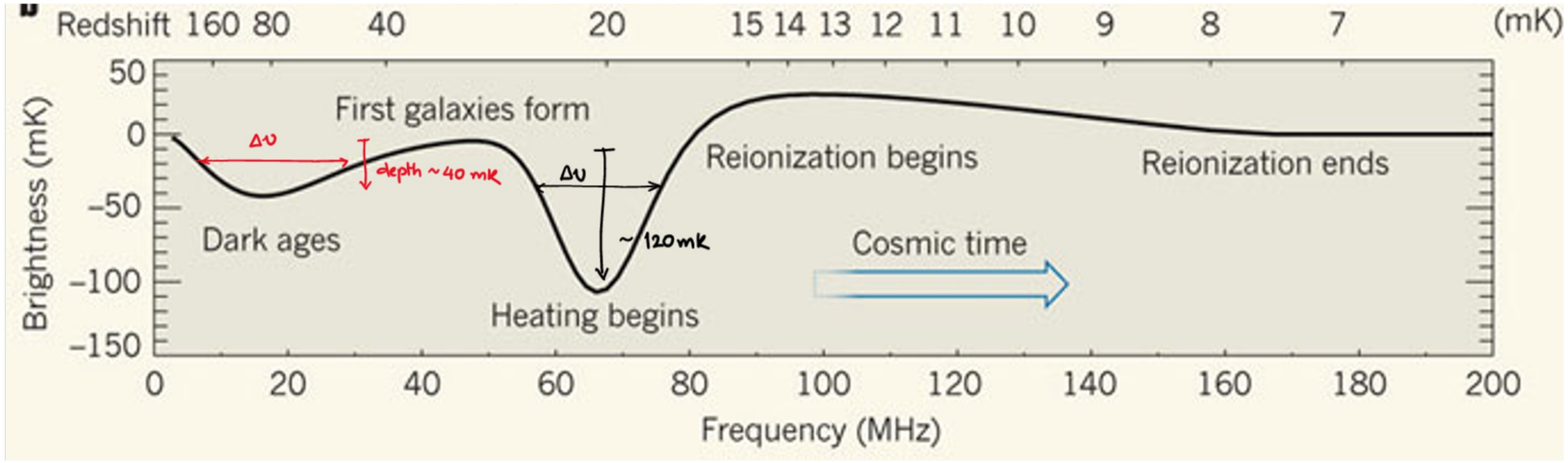


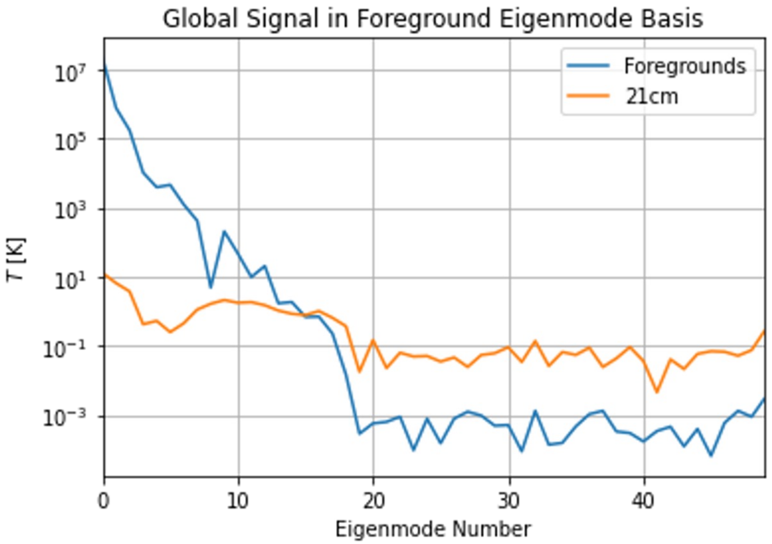
Sample satellite coverage



Preliminary results for 4s integration

Extracting cosmologically interesting signal



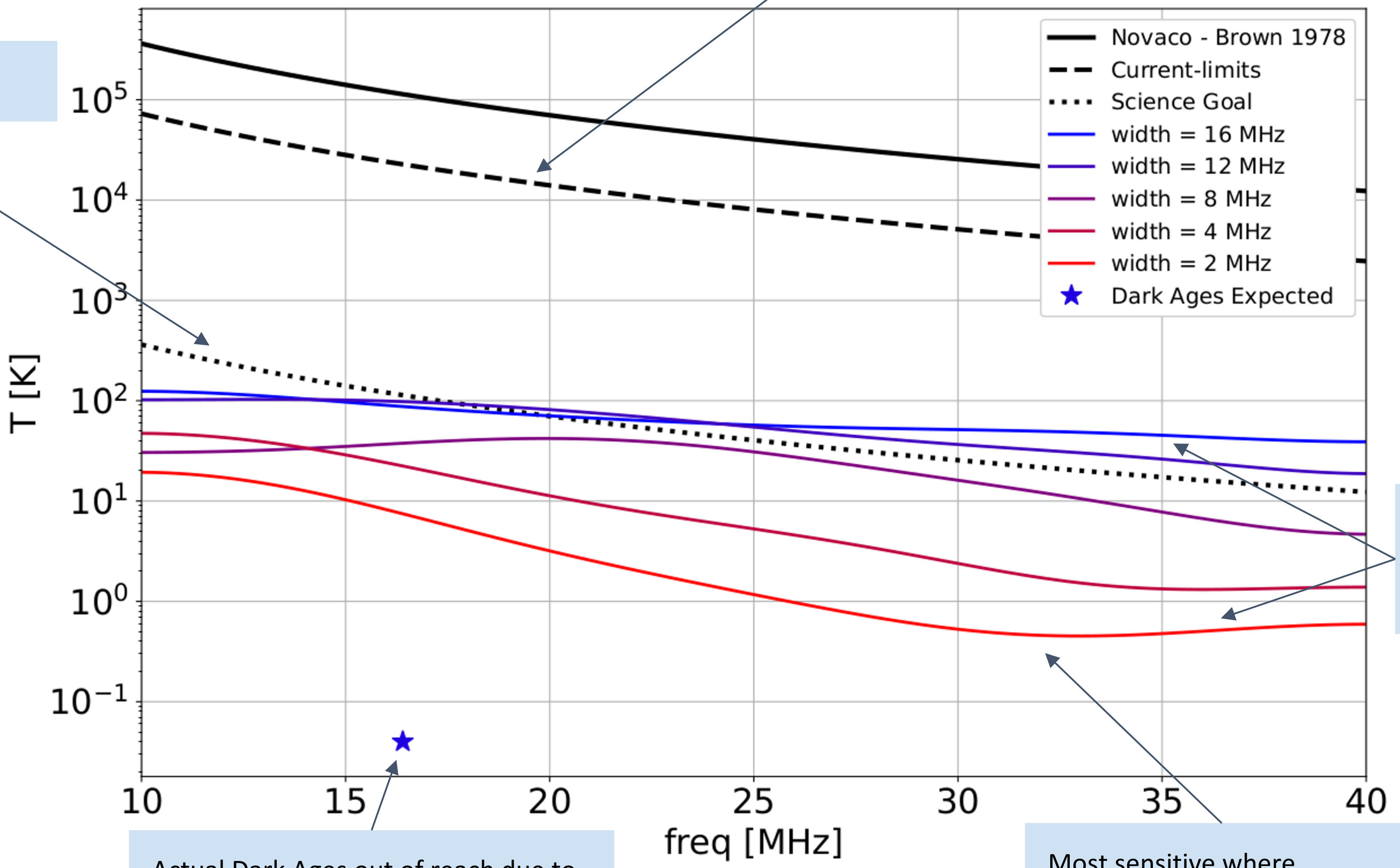


- Traditionally, we rely on spectral smoothness
- Does not work in Dark Ages signal:
  - feature is just too broad
  - Δυ ~ υ
- Instead, assume that fluctuations around the mean foreground shape are drawn from the same distribution as the foreground mean

Sky Monopole Sensitivity plot (preliminary)

Current limits: 20% variations around Novaco - Brown

10^{-3} science goal #4



Narrow features are easier to detect since foregrounds are smooth

Actual Dark Ages out of reach due to chromaticity of dipole antennas

Most sensitive where radiometer is most sensitive

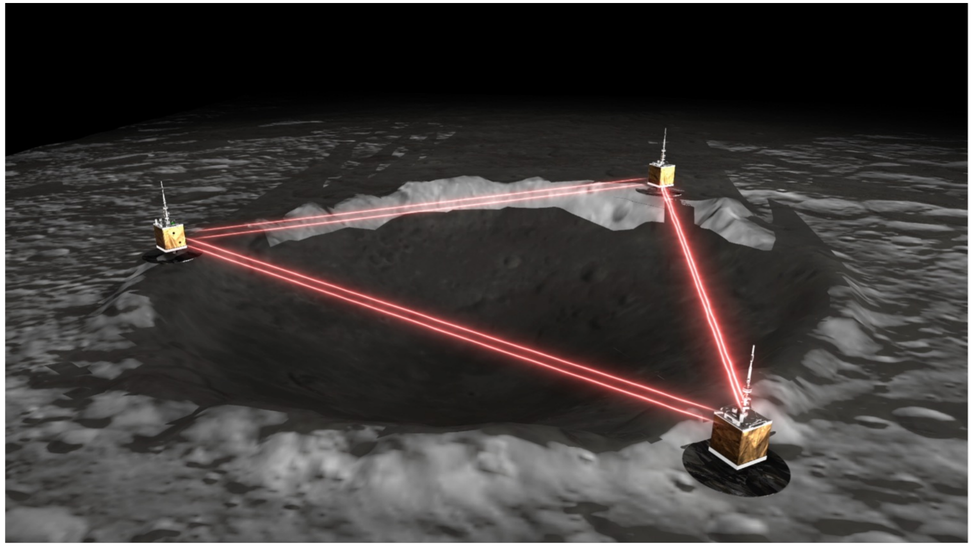
Looking further: future for Physics on the Moon

LuSEE-Night is a pathfinder:

- demonstrate transferable technologies on surviving Lunar night
- make pioneering measurements
- develop strong NASA-DOE partnership

LuSEE-Night will be followed by subsequent experiments:

- Simple LF interferometer
- Large, autonomous, real-time data reduction interferometers
- building on LuSEE-Night technologies



Gravity Wave Concept (courtesy of Karan Jani)

Surface of the Moon is a unique place to do fundamental science beyond Radio Astronomy:

- Deci-Hz gravity waves to fill the gap between Earth and space-based observatories
- Dark Matter searches

LuSEE-Night will teach us how to do all of these

Summary

- **LuSEE Night is in active development in NASA/DOE partnership**
  - Strategic initiative for both agencies
  - UC Berkeley on contract with NASA MSFC
  - Brookhaven National Lab and Lawrence Berkeley Lab funded under DOE MIE
  - CS-3 lander to the lunar farside – manifested with ESA Lunar Pathfinder
    - Lander selection **Q1 2023 – Firefly Aerospace**
    - Instrument delivery **Q4 2024**
    - Landing window **Q1 2026**
  - NASA CS-4 far-field calibration source – selection ~May 2023
  - Radio astrophysics/cosmology pathfinder
    - Quiet corona, galactic foreground, discrete sources and outer planets, cosmology
    - 50 MHz bandwidth Stokes polarization measurements:
      - All 16 correlation products will be measured
      - Novel spectrometer with additional data products
    - Lots of work in progress:
      - Antenna/sensitivity modeling
      - Thermal design in progress
      - Data reduction & map making
- Stay tuned!